QUALITY AND MANAGEMENT

UDC 666.1.053.562:62.001.57:681.3

USE OF MODELING FOR CONTROLLING THE QUALITY OF MANUFACTURED GLASS

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Translated from *Steklo i Keramika*, No. 10, pp. 22 – 24, October, 2006.

Mathematical models of production of sheet glass were developed. The problem of controlling the melting-production problem was formulated. The efficacy of utilizing mathematical models for working out effective actions to improve the quality of the glass was demonstrated.

The most important problem in the quality management system in production of sheet glass is constantly increasing the effectiveness of the manufacturing processes based on data analysis and elaborating the corresponding corrective actions.

Simulated modeling of operation of the manufacturing line is being conducted to determine resources for further improving glass quality and different algorithms for controlling the glass production process are being investigated. Modeling was done with statistical data from operation of the 1LPS line in 2005.

Control of the sheet glass melting-production process is a multicriterial decision-making problem. The penalty function method was used for solving it in [1].

The selected solution is evaluated with a set of criteria which differ in relative importance:

$$F = (Q_g, \Delta De, B, Ri, Ze, Re, Tn, Cu, Bl, \sigma),$$

where Q_g is the gas consumption for glass melting, m^3/h; ΔDe is the change in the density of the glass over 24 h, g/cm^3; B are the melting bubbles (class 1 and 2 defects), number per 10 m^2; Ri is rippling of the glass, evaluated by samples; Ze is waviness of the glass, measured with the Zebra method, deg; Re are the deviations in the reflected grid index, mm; Tn is the thickness nonuniformity of the glass, mm; Cu is the curvature (deviation from planeness), mm; Bl is the bloom effect, g/m^2; σ are the residual stresses in the glass ribbon, nm/cm.

Each local criterion characterizes some local goal of the decisions made. The optimum solution is selected in the region of compromises [2]. Selection of the compromise scheme has not been formalized. The principle of selection of one optimized criterion was used in the study. The gas flow for glass melting, whose minimization in the given glass production plan corresponds to the problem of obtaining the highest gain in production, was selected with the optimized criterion. Restrictions are imposed on the other indicated criteria, and fulfilling them should ensure production of high-quality glass – M0 and M1.

Decision making based on correction of the glass production regime (control) is executed at input of the control object. The value of the density of the glass is established 4 days after an action, while the optical distortions, parameters of the glass, and defects are determined during the current control step (24 h) due to the different inertness of the control channels based on regime variables. The lack of a strong correlation between the output variables (De, B, Ri, Ze, Re, Tn, Cu, Bl, σ), allows combining planning of the density of the glass with prediction of the density several days in advance with the problem of controlling the optical properties and defects in the glass during the current decision-making step.

The glass quality indexes are described by linear regression equations [1] in which the temperature of the gas medium in the furnace based on the readings of dome thermocouples Θ_{gm2}, Θ_{gm6}, Θ_{gm8} along the axes 2nd, 6th, and 8th pair of burners; the temperature of the tin in the float bath bays Θ_{12ba}, Θ_{20ba}; the temperature of the glass entering the float bath Θ_{en}; the temperature of the glass ribbon going out of the float bath Θ_{ex}; the speed of the first edge-forming machine v_{1efm}; the annealing temperature in annealing fur-

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0361-7610/06/0910-0339

nace zones A and B – Θ_a and Θ_b; the slope of the temperature curve along the annealing furnace tunnel a_1.

The restrictions imposed on the properties and flaws of the sheet glass must be fulfilled:

change in the density of the glass over 24 h:

$$|\mathrm{De}\,(i-1) - \mathrm{De}\,(i)| \le \Delta \mathrm{De}_{\max},$$

where De (Θ_{gm6}, Θ_{gm8}, $C_{Fe_2O_3}$, C_{SiO_2}); $i = 2, 3, ...$ is the decision-making step with respect to control;

the optical distortions visible in transient light:

$$\mathrm{Ze}\,(v_{1efm}, \Theta_{12ba}, \Theta_{20ba}, \delta, C_{O_2}) \ge \mathrm{Ze}_{\min};$$

the optical distortions visible in reflected light (grid):

$$\mathrm{Re}\,(\Theta_{en}, \Theta_{12ba}, \Theta_{20ba}, \Theta_{ex}) \le \mathrm{Re}_{\max};$$

the thickness nonuniformity of the glass ribbon:

$$\mathrm{Tn}\,(v_{1efm}, \Theta_{en}, \Theta_{1ba}, \Theta_{12ba}, \delta) \le \mathrm{Tn}_{\max};$$

the deviation from planeness (curvature) of the glass sheet:

$$\mathrm{Cu}\,(\delta, \Theta_{ex}, \mathrm{De}) \le \mathrm{Cu}_{\max};$$

the Bloom effect:

$$\mathrm{Bl}\,(\Theta_{12ba}, C_{O_2}, \Theta_{ex}) \le \mathrm{Bl}_{\max};$$

the residual internal stresses in the glass:

$$\sigma\,(a_1, v_{gr}, \delta) \le \sigma_{\max},$$

where $C_{Fe_2O_3}$ and C_{SiO_2} are the content of Fe_2O_3 and SiO_2 in the glass, %; δ is the thickness of the glass ribbon, mm.

It is necessary to select one of the many decisions on correcting the operating conditions of the equipment from the area defined by the system of restrictions:

$$\Theta_{gm2,\,\min} \le \Theta_{gm2} \le \Theta_{gm2,\,\max};$$

$$\Theta_{gm6,\,\min} \le \Theta_{gm6} \le \Theta_{gm6,\,\max};$$

$$\Theta_{gm8,\,\min} \le \Theta_{gm8} \le \Theta_{gm8,\,\max};$$

$$\Theta_{12ba,\,\min} \le \Theta_{12ba} \le \Theta_{12ba,\,\max};$$

$$\Theta_{20ba,\,\min} \le \Theta_{20ba} \le \Theta_{20ba,\,\max};$$

$$\Theta_{a,\,\min} \le \Theta_a \le \Theta_{a,\,\max};$$

$$\Theta_{b,\,\min} \le \Theta_b \le \Theta_{b,\,\max}.$$

The magnitude of the increase in the controlling effects in each control step should not exceed the values determined by the features of the melting-production process technology:

$$|\Theta_{gm2}(i-1) - \Theta_{gm2}(i)| \le \Delta\Theta_{gm2};$$

$$|\Theta_{gm6}(i-1) - \Theta_{gm6}(i)| \le \Delta\Theta_{gm6};$$

$$|\Theta_{gm8}(i-1) - \Theta_{gm8}(i)| \le \Delta\Theta_{gm8};$$

$$|\Theta_{1ba}(i-1) - \Theta_{1ba}(i)| \le \Delta\Theta_{1ba};$$

$$|\Theta_{12ba}(i-1) - \Theta_{12ba}(i)| \le \Delta\Theta_{12ba};$$

$$|\Theta_{20ba}(i-1) - \Theta_{20ba}(i)| \le \Delta\Theta_{20ba};$$

$$|\Theta_a(i-1) - \Theta_a(i)| \le \Delta\Theta_a;$$

$$|\Theta_b(i-1) - \Theta_b(i)| \le \Delta\Theta_b;$$

$i = 2, 3, 4, ...$.

The restrictions on the shape of the temperature curves of the glass furnace and gloat bath should also be observed:

$$(\Theta_{gm6}(i) - \Theta_{gm5}(i)) \ge \Delta\Theta_{gm56};$$

$$(\Theta_{gm6}(i) - \Theta_{gm8}(i)) \ge \Delta\Theta_{gm68};$$

$$|\Theta_{12ba}(i) - \Theta_{ex}(i)| = \Delta\Theta_{12ex};$$

$$|\Theta_{20ba}(i) - \Theta_{ex}(i)| = \Delta\Theta_{20ex};$$

$i = 1, 2, 3, 4, ...$.

In solving the control (planning) problem, the sheet glass production plan and ribbon thickness are defined. The ribbon drawing rate v_{gr} is determined by a calculation in terms of the planned production with consideration of the ribbon thickness and width. The regime variables not included in statement of the problem are stabilized at levels determined by the process regulations.

Previously elaborated adaptive control models were used to solve the production control problem [1, 3].

In consideration of the above, the following penalty function was obtained:

$$\begin{gathered}
M(t) = (\lambda_1\, abs\,(\min(\mathrm{Re}_{\max} - \mathrm{Re}, 0)) + \lambda_2\, abs\,(\min(\mathrm{Bl}_{\max} - \\
\mathrm{Bl}, 0)) + \lambda_3\,(abs\,(\Delta\Theta_{20ex} - (\Theta_{20ba}(t) - \Theta_{ex}(t)))) + \\
\lambda_3\,(abs\,(\Delta\Theta_{12ex} - (\Theta_{12ba}(t) - \Theta_{ex}(t)))) + \\
(\lambda_4\,(abs\,(\min(\Delta a - abs\,(a(t) - a(t-1)), 0))) + \\
\lambda_5\,(abs\,(\min((\sigma_{\max} + (\delta(t) - 2)) - \sigma, 0))) + \\
\lambda_6\, abs\,(\min(\sigma, 20))) + (\lambda_7\, abs\,(\min(\Delta \mathrm{De}_{\max} - \Delta \mathrm{De}, 0)) + \\
\lambda_8 Q_{gm} + \lambda_9\, abs\,(\min(\mathrm{Ze} - \mathrm{Ze}_{\min}, 0)) + \\
\lambda_{10}\, abs\,(\min(\Delta\Theta_{gm6} - abs\,(\Theta_{6gm}(t-1) - \Theta_{6gm}(t)), 0)) + \\
\lambda_{10}\, abs\,(\min(\Delta\Theta_{gm8} - abs\,(\Theta_{8gm}(t-1) - \Theta_{8gm}(t)), 0)) + \\
\lambda_{10}\, abs\,(\min((\Theta_{6gm}(t) - \Theta_{5gm}(t) - \Delta\Theta_{gm65}), 0)) + \\
\lambda_{10}\, abs\,(\max((\Theta_{8gm}(t) - \Theta_{6gm}(t) + \Delta\Theta_{gm86}), 0))),
\end{gathered}$$

where $M(t)$ is the penalty function in the control step; λ_i is the penalty coefficient; $t = 2, 3, ...$ is the decision-making step with respect to control.

TABLE 1

Index	Manual regime		Control algorithm	
	average value	standard deviation	average value	standard deviation
Density, g/cm^3	2.4965	0.0036	2.5029	0.0037
Zebra, deg	53.0	6.0	57.8	6.0
Gas consumption, m^3/h	5002.0	362.7	4821.0	371.0
Grid (1st section), mm	4.28	1.69	3.25	1.16
Bloom effect, g/m^2	1.250	0.001	0.890	0.220
Thickness nonuniformity (1st section), mm	0.041	0.033	0.042	0.025
Residual stresses, nm/cm	8.98	2.00	8.80	3.40
Curvature, mm	0.026	–	0.009	0.001
Temperature of gas medium in glass furnace, °C:				
along axis of 6th pair of burners	1511.5	18.8	1561.5	–
along axis of 8th pair of burners	1456.5	17.7	1410.4	15.7
Temperature of tin in float bath, °C:				
in 12th bay	798.8	18.1	813.2	–
in 20th bay	603.0	5.0	596.4	–
Temperature of glass ribbon coming out of gloat bath, °C	616.0	5.7	612.5	5.6
Intensity of change in annealing temperature over tunnel length, °C/m	– 4.37	1.7	– 4.34	1.7

Control of the melting-production process using the penalty function algorithm allows conducting the manufacturing process more economically in comparison to manual control: a decrease in consumption of natural gas by approximately 4% is expected. The results of modeling the 1LPS line with 2005 data are reported in Table 1.

As simulation modeling showed, using the proposed control algorithm instead of manually conducting the melting-production process makes it possible to more economically utilize natural gas for melting glass while simultaneously improving its quality.

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